A tablet-based tool for accurate measurement of hand proprioception after stroke

Abstract

Background and Purpose. Proprioceptive deficits in the hand are common following stroke, but current clinical measurement techniques are too imprecise to detect subtle impairments or small changes during rehabilitation. We developed a tablet-based tool to measure static hand proprioception using an adaptive staircase procedure. Here we compare the tablet with other methods in 16 chronic stroke survivors and age-matched controls.

Methods. We quantified proprioception at the metacarpophalangeal joint of the index finger of each hand using three methods: the tablet task, a custom passive motion direction discrimination test (PMDD), and a manual assessment similar to the Fugl-Meyer (F-M) proprioception subsection.

Results. Both the tablet and PMDD found impaired proprioception in the affected relative to the unaffected hand ($p = 0.024$ and 0.028) and relative to the control group ($p = 0.040$ and 0.032), while manual assessment did not. The PMDD had a ceiling effect as movements over 15° were not biomechanically feasible. The tablet and PMDD detected impaired proprioception in 56-75%, and the F-M in only 29%, of patients. PMDD and tablet measures were both correlated with primary tactile sensation, but not manual dexterity.

Discussion and Conclusions. Both tablet and custom PMDD performed better than manual assessment. PMDD may be useful when the deficit is mild or assessment of dynamic proprioception is desired. The tablet, lacking the PMDD’s ceiling effect, could be useful at any level of proprioceptive impairment, and may be preferable if testing or clinician training time needs to be minimized, or pain or spasticity is present.

Video abstract available. See Video, Supplementary Digital Content 1.

Keywords: Proprioception; Stroke; Hand; Somatosensory disorders; Technology; Psychometrics

Abbreviations:

F-M: Fugl-Meyer

PMDD: Passive movement direction discrimination

MP: metacarophalangeal joint

MMSE: Mini Mental State Exam

MRC: Medical Research Council scale for muscle strength

BBT: Box and Block Test

PPT: Purdue Pegboard Test

Introduction

The proprioceptive senses, including static position sense and movement sense or kinesthesia[1], are critical for accurate movement[2,3], but often impaired following stroke[2,4–9]. Deficits in hand proprioception are associated with functional impairment[10–12], including poor motor recovery[13–15] and reduced ability to complete tasks of daily living[2,16,17]. Clinicians often need to assess proprioception to determine the extent of neurological injury, manage therapy plans, and evaluate progress[18,19]. The detection of proprioception deficits in individuals post-stroke has important clinical ramifications considering rehabilitation interventions are based on accurate identification of deficits[19] and the ability to demonstrate rehabilitation progress. For example, proprioceptive deficits detected immediately after stroke can help predict arm function one year later[20], which may influence rehabilitation choices. Failure to detect proprioception deficits may leave a substantial number of patients who require treatment not receiving it, or not receiving appropriate treatments and thereby wasting treatment time[19]. Current clinical methods, however, are too subjective and poorly standardized to detect subtle deficits or changes in proprioception[21,22].

Current options for clinical testing of proprioception deficits following stroke are quite limited because there is no single standardized measure that is generally accepted[22,23]. Options include the proprioception subsection of the Fugl-Meyer (F-M)[24], passive movement direction discrimination (PMDD), and position matching, all of which entail subjective judgments by the clinician and poor standardization of the testing procedure. Even within standardized clinical assessments such as the Rivermead Assessment of Somatosensory Performance[23], proprioception is determined subjectively. The proprioception subsection of the F-M is arguably the most common clinical test, and could be considered the *de facto* gold standard; however, the sensory scales of the F-M perform poorly in the stroke population, with Lin et al. (2004) reporting a significant ceiling effect and low to moderate validity and responsiveness[25]. This and other subjective tests continue to be implemented clinically[26], but more objective tests have been developed in the research setting. Carey et al. (2002) used an apparatus of protractors and forearm splints to conduct a wrist angle matching task[19], and more recent applications have made use of sophisticated robotics to generate quantifiable metrics for proprioception and kinesthesia[9,27–30]. For example, Goble et al. (2009) used a bimanual robotic system to accurately execute an elbow-angle matching task[31]. Semrau et al. (2013) assessed upper limb kinesthesia with psychometric techniques implemented in a robotic system as well[32]. These measures provide more sensitive and objective data regarding proprioception; indeed, motor control research has applied these methods to understand somatosensory contributions to movement in healthy subjects[33–36]. Unfortunately, robotic methods have limited clinical utility due to costs associated with the equipment, limited portability, and the considerable training required.

As an alternative to both subjective clinical tests and costly robotic assessments of proprioception, we developed a tool that requires only a computer tablet and hand positioning stand (Fig. 1A)[37]. The subject makes a series of judgments about the location of their unseen stationary index finger in relation to elements displayed on the tablet[37]. This allows us to determine proprioceptive bias (perceptual boundary) at the metacarophalangeal (MP) joint of the index finger in the plane of adduction/abduction, chosen because of its importance for fine motor skill such as a key grip/pinch of small objects between the thumb and index finger.

In healthy adults, the tablet method had better test-retest reliability, inter-rater reliability, and construct validity than two common clinical methods, passive movement direction discrimination (PMDD) and matching, which we customized to reduce subjectivity[37]. While the tablet performed well in healthy adults, its utility in stroke survivors is unknown. After a unilateral cortical or subcortical stroke, proprioception in the contralateral (“affected”) hand may be more impaired than in the ipsilateral (“unaffected”) hand. Here we asked whether the tablet could detect proprioceptive differences between the hands in chronic stroke survivors that were more extreme than between the hands of healthy age-matched controls. We compared the tablet with the custom PMDD[37] and with a proprioception subsection of the F-M[24] modified to assess the index finger along with the thumb. Because even the “unaffected” hand often experiences deficits post-stroke[38], we also compared the affected hand to the control group directly. Finally, we compared the tablet and PMDD to deficits in primary tactile function and manual dexterity[39].

Methods

Subjects

32 subjects completed the study, 16 with stroke and 16 without. All reported they were free of visual impairments and severe or uncontrolled cardiovascular, pulmonary, renal, neurological, or psychiatric conditions. Subjects were screened for serious cognitive deficits with the Mini Mental State Exam (MMSE)[40]. Stroke subjects were screened for hemispatial neglect with the star cancellation task[41]. Procedures were approved by Indiana University Bloomington's Institutional Review Board. All subjects gave written informed consent.

Subjects with stroke completed the MMSE, star cancellation test, and Medical Research Council (MRC) muscle testing[42] of an index finger muscle, first dorsal interosseous (FDI), in that order. Proprioception testing was performed next, with the custom tablet task[37], PMDD[37], and manual assessment based on the F-M[24] administered in random order. We then obtained patients' fine touch[b] and two-point discrimination[b] thresholds and performed the box and block test of manual dexterity[39] (BBT)[c], followed by the F-M upper extremity motor section[24]. Most subjects completed the session in ~90 minutes.

Age-matched control subjects completed the MMSE and Edinburgh handedness inventory[43], then the proprioception tablet task and PMDD in random order, and finally the Purdue Pegboard Test (PPT)[d] of manual dexterity[44]. The session required ~45 minutes.

Proprioception measures

Tablet task. With eyes closed, the subject's hand was positioned in the stand by the experimenter (Fig. 1A). The subject was asked to press down firmly with their index finger and then relax, to control for muscle thixotropy[1]. After the experimenter positioned the tablet[a] over the hand layer, the subject was asked to open their eyes. Subjects were familiarized with the task by a training sequence of the custom application. Subjects were instructed not to move their hand during the test.

< *Figure 1 about here* >

For each trial, the tablet displayed two colored regions, with one end of the dividing line fixed over the MP joint. Subjects reported which color they felt was over the center of their index fingertip. The angle of the dividing line changed every trial in an adaptive staircase algorithm based on Parameter Estimation by Sequential Testing[45], which has been implemented in robotic measures of proprioception[33]. The test consisted of two staircases, with line angle beginning at 30° left and right of true index finger angle. Initial step size was 10°. In a staircase beginning 30° to the left of true finger position, most subjects perceive that the dividing line is left of their index finger and choose the color to the right of the line. The line would then move 10° to the right, and many subjects would still choose the color on the right. However, as the line approaches true finger position, subjects become more uncertain and eventually choose the color to the left of the line. Whenever the subject's choice of color reversed, the line reversed direction and step size decreased by half to yield more measurements near the subject's perceptual boundary (the angle at which the subject is equally likely to choose either color). Each staircase terminated after four reversals. For most subjects, this resulted in ~10 trials per staircase. The complete test, including positioning the subject in the apparatus and training, took 2-3 minutes.

Each test resulted in 8 reversal angles (4 per staircase). We averaged these 8 angles to obtain an estimate of perceptual boundary, analogous to spatial bias in perceived joint angle. We previously found this corresponds closely to the perceptual boundary determined by fitting a logistic model, and that two staircases yield data nearly as reliable as six staircases[37]. Because we have no evidence to suggest a rightward bias in proprioception is better or worse than a leftward bias, group analysis used the absolute value.

For detailed testing protocol, see Document, Supplemental Digital Content 2.

PMDD was tested in both groups to assess dynamic proprioception at the MP joint of the index finger. Subject positioning was the same as the tablet task, except the eyes were closed throughout and the hand was pronated on a paper template (Fig. 1B). Once correctly positioned, subjects were asked to press down firmly with their index finger and then relax, to control for muscle thixotropy[1]. The initial passive movement amplitude tested was 5°. Each amplitude was tested 6 times, with three rightward and three leftward movements in random order. If a subject was correct on all 6 movements of 5° amplitude, the movement amplitude was reduced to 2.5°. If a subject made an error at 5°, amplitude increased to 10°. The procedure took ~5 minutes per hand.

PMDD threshold was defined as the smallest of 1.25, 2.5, 5, 10, or 15° movement amplitudes that the subject responded correctly for all 6 movements. PMDD data were right-censored; i.e., many subjects made errors even on 15° movements, especially on the affected hand in the stroke group, but larger movements were not biomechanically feasible. PMDD threshold was recorded as "15+" (Table 1) for these subjects, but a value of 15° was substituted for group analyses.

Manual assessment (Stroke Group only). Following the standard F-M proprioception subsection procedure, we tested thumb flexion-extension at the interphalangeal joint. In addition, we tested right and left movements of the index finger (abduction/adduction at the MP joint) to be consistent with the PMDD and tablet tasks, using the same sequence of steps as the thumb test. Standard F-M scoring of 0, 1, or 2 was applied for both versions[24].

Analysis

Wilcoxon rank sum tests were performed to test whether median between-hand differences in the stroke group were more extreme than in the control group on the tablet or PMDD. The differences analyzed were affected minus unaffected hand for the stroke group, and nondominant minus dominant hand for the control group. Wilcoxon signed rank tests were performed to test whether median two-point discrimination, fine touch, or BBT scores were worse in the affected than the unaffected hands in the stroke group, whether median PPT scores differed between dominant and non-dominant hands in the control group, and whether tablet and PMDD differed between the stroke group's affected or unaffected hand and the control group. For the latter stroke-control comparisons, we used the average of control subjects' dominant and non-dominant hands, as we found no between-hand difference and conflicting literature as to whether such a difference should be expected[46–53].

For both the tablet method and PMDD, we computed sensitivity, specificity, and positive and negative predictive values, treating the manual assessment based on the F-M proprioception subsection as the gold standard. Because two of the stroke subjects lacked the manual assessment, only 14 stroke subjects were included in the sensitivity analyses. We identified stroke subjects with proprioceptive deficits (“positives”) in two ways. First, we compared each stroke subject’s tablet or PMDD value in their affected hand versus their unaffected hand: if the affected hand had a worse (higher) value than the unaffected hand, that subject was considered a positive. Second, we compared the tablet or PMDD measurement of each stroke subject’s affected hand with the mean control group value: stroke subjects with values that exceeded the control group mean plus 95% confidence interval were considered positives[23,27,32,54].

Spearman rank correlations were computed to assess the relationship between tablet or PMDD and each of two-point discrimination threshold, fine touch threshold, and BBT score in the stroke group. Affected hand values were divided by unaffected hand values to normalize for individual variation that may be unrelated to the stroke. Bonferroni corrections were performed to compensate for multiple comparisons. All hypothesis tests were performed two-tailed.

Results

The 16 stroke subjects (8 female, age 64.1 ± 15.2 years) had experienced unilateral ischemic or hemorrhagic cortical or subcortical stroke with motor deficits at least 6 months prior (Table 1).

< Table 1 about here >

Average time post stroke was 7.4 ± 7.6 years (mean ± standard deviation). Motor function of the impaired hand averaged an MRC[42] grade of 3.6 ± 2.0, indicating moderate impairment. Subjects S-01 and S-02 completed the experiment before the manual assessment of proprioception was added, so analysis of this parameter excluded these subjects. Subjects S-05 and S-15 lack data for the motor assessments (BBT and F-M UL) because of limited shoulder mobility due to arthritis and history of a torn rotator cuff, respectively. Analysis of the motor variables therefore excluded these two subjects. The 16 age-matched controls had no history of stroke (9 female, age 65.7 ± 14.4 years); each control subject was within 5 years of a particular stroke subject's age (Table 2).

< *Table 2 about here* >

Comparing proprioception across hands

Tablet. Stroke group: Proprioceptive bias in the affected hand was worse than in the unaffected hand (Fig. 2) for 12 of 16 stroke subjects. Median bias was 15.5° and 9.2° in the affected and unaffected hands, respectively. Control group: Proprioceptive bias on the tablet was worse in the non-dominant hand compared to the dominant hand for 5 of 16 subjects. At the group level, median tablet bias was 9.2° and 10.7° in the non-dominant and dominant hands, respectively. The between-hand difference was greater in the stroke group than the control group (W = 203.5, Z = -2.26, p = 0.024). This suggests that between-hand differences are greater in the stroke group (median difference 6.3°) than in controls (1.5°) (Fig. 3A).

< *Figure 2 about here* >

< *Figure 3 about here* >

PMDD. Stroke group: the PMDD showed a higher threshold (worse proprioception) in the affected than the unaffected hand for 9 of 16 stroke subjects. All 9 were among those found by the tablet to have worse proprioception in their affected hand. Because we dealt with the PMDD ceiling effect by substituting 15° for “15+”, group PMDD values likely underestimate true threshold[55]. Median values were 15° and 5° in the affected and unaffected hands, respectively. Control group: The PMDD showed worse proprioception in the non-dominant hand for 3 of the 16 control subjects; median PMDD threshold was 5° for each hand. The between-hand difference in PMDD was greater in the stroke group than the control group (W = 206, Z = -2.20, p = 0.028), suggesting that between-hand differences are greater in the stroke group (median difference of 10°) than in controls (0°) (Fig. 3B).

<u>Manual assessment of proprioception (stroke group only).</u> The manual assessment showed worse proprioception on the affected side in only 2 of the 14 stroke subjects at the thumb, and in 4 of the 14 stroke subjects at the index finger. Manual assessment score did not differ significantly across hands for either the thumb (W = 3, Z = 1.41, p = 0.31) or index finger (W = 10, Z = 2.0, p = 0.09). If we consider the manual assessment to be the *de facto* gold standard measure of proprioception, and define tablet and PMDD deficits by comparing the affected to the unaffected hand, then sensitivity of both the tablet and PMDD is 0.75, with 7 and 4 false positives, respectively (Table 3A).

< Table 3 about here >

Comparing proprioception in affected hand to control group

Comparing the affected hand of the 16 stroke subjects to the control group, 9 stroke subjects had impaired proprioception according to the tablet test, and 12 had impaired proprioception according to the PMDD. Eight of the 9 impairments identified with the tablet were also identified by the PMDD. Proprioception was significantly worse in the stroke group's affected hand compared to the control group, according to both the tablet (W = 209, Z = -2.05, p = 0.040) and the PMDD (W = 207.5, Z = -2.15, p = 0.032). If we consider manual assessment the *de facto* gold standard measure of proprioception, and define tablet and PMDD deficits by comparing the affected hand to controls, then sensitivity of the tablet is 0.75 with 5 false positives, and sensitivity of the PMDD is 1 with 6 false positives (Table 3B).

Comparing the "unaffected" hand of the 16 stroke subjects to the control group, 4 of the stroke subjects had impaired proprioception according to the tablet, and 5 had impaired proprioception according to the PMDD. However, as a group, the stroke subjects' unaffected hand was not significantly different than controls for either the tablet (W = 257, Z = -0.25, p = 0.81) or PMDD (W = 255.5, Z = -0.31, p = 0.76). This suggests that some individuals in the stroke group had proprioceptive deficits in their "unaffected" hand, but the group overall did not.

Primary tactile and manual dexterity measures

Median two-point discrimination threshold in the stroke group was 7mm and 2.5mm in the affected and unaffected hands, representing a significant difference (W=6, Z = -2.59, p=0.01; Fig. 3Bi). Median fine touch threshold did not differ across hands (W=9, Z = -1.26, p=0.21); median value was 3.61 (0.4g of force) in both (Fig. 3Bii). Stroke subjects achieved a median BBT score of 50.5 and 23.5 in the unaffected and affected hands, respectively (Fig. 3Ci), representing a significant difference (W=105, Z = 3.30, p<0.001). Control subjects achieved a median PPT score of 12.5 and 13 in the non-dominant and dominant hands, respectively (Fig. 3Cii), representing a non-significant difference (W=96.5, Z = 1.48, p=0.14).

For stroke subjects, between-hand percent difference in tablet bias was positively correlated with two-point discrimination threshold (r=0.55, p=0.04; Fig. 4Ai). However, percent differences in tablet bias were not significantly correlated with either fine touch threshold or BBT (r=0.29, p>0.1; r=-0.37, p>0.1, respectively; Fig. 4Aii-iii). Between-hand percent differences in PMDD threshold were positively correlated with two-point discrimination (r=0.68, p=0.006; Fig. 4Bi) and fine touch (r=0.88, p<0.001; Fig. 4Bii), but not with BBT (r=-0.038, p>0.1; Fig. 4Biii).

< *Figure 4 about here* >

Discussion

Here we compared three proprioception measures in chronic stroke survivors. Only the tablet and PMDD found median differences between the hands relative to controls, although the PMDD had a ceiling effect. Whether comparing the affected hand to the unaffected hand or to controls, the tablet and PMDD identified more stroke subjects with proprioceptive impairment than the manual assessment did. PMDD and tablet measures were each correlated with primary tactile sensation, but not with manual dexterity.

Detecting proprioceptive deficits

Assessment is complicated by proprioception’s multiple sub-modalities, e.g. static position sense, passive motion sense, sense of effort[1]. The PMDD and the proprioceptive subsection of the F-M measure passive movement sense; matching tests static position sense after active movement, or in some cases subjects are asked to actively match a passive movement[56] . Common clinical versions of these tests, such as the manual assessment performed here, are known to be coarse, subjective, and poorly standardized[22,57,58]; they fail to control for muscle thixotropy, the contraction history of the muscle, or movement speed and amplitude, all of which affect proprioception[1,22,59].

Proprioceptive assessments that require movement may be confounded by pain[60], spasticity, and in the case of tests requiring active movement, motor deficits. For example, a patient with pain may tense up with movement, providing extra stimulation to spindles and leading to over-estimation of proprioceptive function. The patient may have less pain on a return visit, yielding a more accurate proprioceptive estimate but erroneously indicating a worsening of proprioception since the first visit. Tests involving movement also carry the risk of a ceiling effect, as the PMDD showed in the present study. In a patient who makes errors at the largest feasible movement amplitude, slight improvements due to rehabilitation cannot be detected. For these reasons, a static test of proprioception may be a useful supplement or replacement for movement-based tests. The brain continues to integrate background spindle activity, joint receptors, and skin stretch input even when the body is stationary[1]; indeed, static proprioception is critical for accurate motor control as it allows the brain to estimate the limb's starting position for motor planning[1]. Animal research indicates static and dynamic position information depend on the same neural networks[61,62].

Between-hand differences in the stroke group relative to controls were detected by the tablet and PMDD, but not the manual assessment. The tablet and PMDD both identified more stroke subjects as having an impairment relative to the unaffected hand than the manual assessment did. Consistent with the literature[38], some stroke subjects had proprioceptive deficits in their "unaffected" hand according to both the tablet and PMDD, but not the manual assessment. This may have caused the between-hand approach to underestimate the true number of stroke subjects with proprioceptive deficits, although deficits in the “affected” hand can generally be expected to be more severe than in the “unaffected” hand. The stroke-control comparison supplements the between-hand analysis. Both the tablet and PMDD detected significant differences between the affected hand and the control group, and both identified more stroke subjects with deficits than the manual assessment did. However, the stroke-control comparison also has limitations. Namely, neither the tablet nor PMDD has large normative data sets for comparison, and using a small age-matched control group to define deficits must be interpreted with caution.

These results, combined with the sensitivity analysis, suggest the tablet has greater sensitivity to detect proprioception deficits compared to the manual assessment. Although these initially appear as false-positives, many patients who showed deficits with the tablet or PMDD scored full points in both hands on the manual assessment, both the standard F-M subsection version at the thumb, and the alternate version at the index finger. This suggests manual assessment lacks sensitivity to detect more subtle proprioceptive deficits even though it is often considered the ‘gold-standard’ clinical assessment. As a result, in the clinical setting, manual assessment may not detect subtle proprioceptive deficits or changes due to rehabilitation. These findings are consistent with Carey et al.[19], who demonstrated the lack of abnormal outcomes on clinical measures compared to newer standardized tests. Given the increased demands to evaluate progress with rehabilitation interventions, a more quantifiable measure of proprioception including the tablet measure may overcome these current clinical challenges.

The tablet offers an advantage over the manual assessment or other PMDD tests in terms of clinician training time. To use the tablet test, the clinician only needs to know how to place the hand on the stand and run the app. The test itself is automated from that point, which likely contributed to the greater reliability we previously found relative to the PMDD or matching[37]. In contrast, to use the PMDD or manual assessment correctly, the clinician needs skill at grasping the thumb or finger without giving pressure cues, and moving the thumb or finger at a slow but consistent speed, all while following a random sequence of movement directions and recording subject response.

Relationship of proprioception to primary tactile and motor assessments

Two-point discrimination and manual dexterity in the stroke group showed clear impairments in the affected hand, while fine touch threshold did not. The PMDD and tablet measurements were both correlated with two-point discrimination, but only PMDD was related to fine touch threshold. The tablet impairment was relatively clustered, which may have limited our ability to detect correlations. Future studies will need to examine tablet and PMDD in larger samples to determine how strongly these measures are related to tactile assessments.

F-M upper limb scores ranged from 8 to 64 in the stroke group, suggesting considerable variation in motor impairment. The lack of correlation between proprioception and BBT was not necessarily surprising. This is consistent with several previous studies that found no relationship between proprioceptive and motor deficits after stroke[10,63].

Study limitations

To simplify comparisons, both the tablet and PMDD measurements were applied with the hand pronated and fingers slightly spread. Measurements in these conditions may not generalize to other postures[1] or to extreme finger angles[64]. Also unknown is how proprioceptive deficits measured at the index finger would compare to other joints such as wrist and elbow. While the hand-positioning stand could be modified to apply the tablet test at other finger joints and even the wrist, the need for the patient to gaze directly at the tablet when placed over the joint being tested precludes the use of this method at the shoulder or elbow. However, this limitation does not take away from the clinical utility of the test when manual assessment is insufficiently sensitive or functional deficits are most noticeable in the hand. In other words, if a patient has such severe proprioceptive deficits that the shoulder and elbow are substantially affected, then manual assessment is likely sufficient to detect the problem. The greatest utility of the tablet test is in cases where the proprioceptive deficit is more subtle and could be overlooked, which would result in the patient not receiving needed treatment.

While the absence of movement in the tablet test clearly offers advantages, the dependence on vision creates a limitation. The test would not be valid for subjects with visual impairments or neglect. Subjects were not tested for color vision; some subjects called the yellow color green, or the pink color purple, but yellow and green were never paired with each other, nor were pink and purple, so there was no potential for the experimenter to press the wrong button. It is possible that slight luminance differences between the colors, or differences in subjects' color perception, could make one color easier to see than the other of a given pair, which might influence the subject's choice. However, this influence would be limited to increasing noise, not proprioceptive bias, as the placement of each color in the left vs. right position was randomized.

Conclusion

Both the tablet and custom PMDD performed better than manual assessment in detecting proprioceptive deficits. PMDD may be useful when the deficit is mild or assessment of dynamic proprioception is desired. The tablet, lacking the PMDD's ceiling effect, could be useful at any level of proprioceptive impairment, and may be preferable if testing or clinician training time needs to be minimized, or pain or spasticity is present.

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Suppliers

[a] Samsung Galaxy Tab Pro 12.2

[b] Baseline Evaluation Instruments, White Plains NY

[c] Model 7531, Sammons Preston

[d] Lafayette Instrument

Supplemental Digital Content

SDC1: video abstract

Fig. 1. Methods for Tablet and PMDD tasks. A. Tablet task. i. Subject was seated with the hand positioned on an angled stand beneath the tablet. **ii.** Tablet display viewed by subject. Circle represents index finger MP joint location, and subject was asked to report which color appeared to be over the center of their index fingertip. Three pairs of colors were used in random order: red/blue, yellow/purple, and green/pink. Angle of the line dividing the two colors changed every trial according to the subject’s responses, using an adaptive staircase algorithm. **iii.**

Schematic of the custom 3D-printed tablet stand. The tablet frame is hinged to the hand layer so that the tablet is correctly positioned over the hand, completely blocking subjects' view of their hand. The hand layer contains depressions for consistent positioning of the hand. **iv.** With subject's eyes closed, the experimenter positioned the subject's pronated hand in the hand layer, with the index finger in a depression angled at 55° to the horizontal and the MP joint on a tactile marker. The elbow was bent about 90° and slightly in front of the body, with the forearm resting on the table. The hand was ~20cm in front of the body and centered with the midline. **B. PMDD task. i.** Subject was seated with eyes closed in front of a paper taped to the table at body midline. **ii.** Subject's index finger was taped to a custom 3D-printed stick with raised tabs at the end for the experimenter to grasp. Tape was placed at two locations along the index finger to reduce twisting during passive movement. **iii.** Paper chart to guide the experimenter. Subject's hand was placed in the appropriate hand outline, with the index finger pointing along a dark line 55° to the horizontal. Lines indicating 10°, 5°, 2.5°, and 1.25° deviations from the dark line guided the experimenter in moving the subject's index finger left or right by varying step sizes. Experimenters were trained to count 2 seconds between each 1.25° line for a movement speed of about 0.062°/s[65]. When each movement was completed, the subject was asked, "Did I move your finger left or right?" After the subject's response was recorded, the experimenter moved the index finger back to neutral before beginning the next movement.

Figure 2. A-C. Three examples of tablet task performance in the stroke group (S-01, S-02, and S-03). **i.** Sequence of line angles tested across trials in the unaffected hand. **ii.** Sequence of line angles tested across trials in the affected hand. Zero on the x-axis represents true finger angle. Bias angle was calculated by averaging the eight reversal angles in the set of two staircases.

Figure 3. Comparing median values in the stroke and control groups. A. Proprioception measures. According both the tablet method (**i**) and the PMDD (**ii**), between-hand difference in proprioception (thick dotted line) was greater in the stroke group than the control group. This suggests that stroke subjects' worse results in the affected vs. unaffected hand are more extreme than the normal difference seen between hands in controls. Affected hand was also significantly worse than mean control values for both the tablet and PMDD. **B. Tactile measures. i.** Two-point discrimination was significantly worse in the affected hand compared to the unaffected hand. **ii.** Fine touch did not differ significantly across hands in the stroke group. **C. Manual dexterity measures. i.** Patients were significantly impaired at the Box and Block test with their affected hand compared to their unaffected hand. **ii.** Control subjects were no better at the Purdue Pegboard test with their dominant hand compared to their nondominant hand. *Significantly different at $p < 0.05$. Error bars represent 95% confidence intervals.

Figure 4. Comparing proprioception measures to tactile and motor measures in the stroke group. A. Absolute value of tablet task bias in the affected hand divided by the unaffected hand. Values greater than 1 indicate the affected hand was more biased than the unaffected hand. **B.** PMDD threshold in the affected hand divided by the unaffected hand. Values greater than 1 indicate the affected hand had worse passive movement detection than the unaffected hand. **i.** Two-point discrimination in the affected hand divided by the unaffected hand. Values greater than 1 indicate the affected hand had worse discrimination than the unaffected hand. Subjects with worse proprioception by either measure had worse two-point discrimination ($p < 0.05$). **ii.** Fine touch threshold in the affected hand divided by the unaffected hand. Values greater than 1

indicate the affected hand had worse fine touch detection than the unaffected hand. Subjects with worse PMDD scores had worse fine touch detection ($p < 0.01$), but there was no correlation with tablet performance. **iii.** Box and block score in the affected hand divided by the unaffected hand. Smaller values indicate worse manual dexterity in the affected hand compared to the unaffected hand. Proprioception by either measure was not significantly correlated with BBT performance. Each circle represents one stroke subject.

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Table 1

Table 1. Stroke Group subject characteristics and results for each hand.

	Age	Sex	Years since stroke	Description of stroke	MRC grade	Tablet bias (°)	PMDD threshold (°)	F-M proprio: Thumb	F-M proprio: Index	Fine touch threshold	Two point discrimination (mm)	Box and Block test	MRC grade	Tablet bias (°)	PMDD threshold (°)	F-M proprio: Thumb	F-M proprio: Index	Fine touch threshold	Two point discrimination (mm)	Box and Block test	F-M Upper Limb
					UNAFFECTED SIDE								AFFECTED SIDE								
S-01	55	M	3.4	Anterior L MCA ischemic	5	-21.3	1.25	~	~	3.61	3	76	4	-27.8	15+	~	~	6.65	20	17	55
S-02	85	M	2.5	Acute infarction of left thalamus	5	6.7	2.5	~	~	3.61	4	50	5	11.9	10	~	~	3.61	8	34	62
S-03	59	F	10.0	Left pontine ischemic cerebral infarct s/p basilar occlusion	5	-8.8	5	2	2	4.31	2	68	5	17.0	1.25	2	2	3.61	3	39	51
S-04	87	F	2.0	Right MCA ischemic	5	19.2	5	2	2	3.61	4	61	5	35.8	10	2	2	3.61	4	57	64
S-05	68	F	15.9	Unknown	5	-5.6	2.5	2	2	4.31	2	~	5	-15.5	15+	2	2	4.56	30	~	~
S-06	43	F	7.4	unknown	5	-5.0	2.5	2	2	2.83	1	57	0	-32.0	15+	1	1	6.65	30	0	18
S-07	82	M	2.9	Right Lacunar	5	-10.6	5	2	2	4.31	2	53	5	-9.2	1.25	2	2	3.61	2	45	60
S-08	55	M	3.4	Perioperative hemorrhagic event	5	1.3	5	2	2	3.61	3	51	3	1.9	15+	1	1	5.07	35	6	46
S-09	53	M	2.5	Right Lacunar	5	-3.3	1.25	2	2	3.61	1	42	2	-6.9	1.25	2	2	3.61	6	1	46
S-10	54	M	1.3	Right MCA CVA	5	-25.2	5	2	2	4.31	1	47	0	-27.2	15+	2	1	6.65	15	0	8
S-11	31	M	13.3	unknown	5	-9.2	2.5	2	2	3.61	1	57	4	-8.8	1.25	2	2	2.83	1	23	51
S-12	69	F	7.1	Right MCA CVA	5	-17.7	10	2	2	3.61	3	45	5	20.6	15	2	2	3.61	8	30	47
S-13	66	M	1.1	L MCA ischemic, L basal ganglia hemorrhage	5	-10.6	10	2	2	3.61	4	42	5	4.5	10	2	2	3.61	4	32	64
S-14	76	F	18.2	Ischemic	5	-6.1	15+	2	2	4.31	10	26	4	-10.6	15+	2	2	4.31	35	24	51
S-15	70	F	25.9	Unknown	5	-31.9	15+	2	2	3.61	10	~	5	-18.4	15+	2	1	3.61	4	~	~
S-16	72	F	0.9	L internal capsule CVA	5	7.5	10	2	2	3.61	2	44	1	-22.0	15+	2	2	3.61	6	0	13

MRC = Medical Research Council grade of muscle strength (5 is best). Tablet bias: closer to zero is better. Negative values signify a leftward bias. PMDD = passive movement direction discrimination (1.25 is best). F-M proprio = Fugl-Meyer proprioception subsection in the thumb or comparable manual assessment of index finger (2 is best). Fine touch and two-point discrimination thresholds: smaller is better. Box and Block Test: number of blocks transferred in 1 minute (higher is better). F-M UL = Fugl-Meyer upper limb section (higher is better). ~ = data unavailable.

Table 2

Table 2. Control Group subject characteristics and results for each hand.

	Age	Sex	Edinburgh handedness inventory	Tablet bias (°)	PMDD threshold (°)	Purdue Pegboard Test	Tablet bias (°)	PMDD threshold (°)	Purdue Pegboard Test
				DOMINANT			NONDOMINANT		
C-01	59	M	29	8.1	2.5	13.3	-5.3	2.5	14.3
C-02	83	F	95	-26.9	15	12.7	-27.0	5	12.0
C-03	58	F	100	-13.6	15	15.7	2.2	5	16.3
C-04	84	F	95	-24.1	2.5	12.7	13.0	2.5	11.0
C-05	69	M	95	9.2	2.5	12.3	-8.8	1.25	11.0
C-06	47	F	85	3.0	2.5	15.0	1.9	1.25	13.0
C-07	79	F	-100	18.4	5	10.7	13.8	10	9.7
C-08	59	M	28	1.4	2.5	10.3	-0.2	2.5	12.3
C-09	52	M	94	-9.2	5	12.7	-1.9	5	15.3
C-10	59	F	69	-10.6	1.25	13.0	-12.5	5	13.7
C-11	28	M	100	6.4	5	14.0	10.8	2.5	11.7
C-12	68	F	100	-4.3	15	14.0	-15.6	5	12.7
C-13	65	M	85	-10.3	2.5	14.3	-4.7	5	12.3
C-14	78	F	100	-8.4	5	13.0	-5.3	5	12.3
C-15	72	F	100	-15.5	10	14.3	-15.2	15	13.7
C-16	73	F	95	4.8	2.5	11.7	15.8	5	8.7

Tablet bias: closer to zero is better. PMDD = passive movement direction discrimination (1.25 is best). Purdue Pegboard Test: average number of pegs placed in 30s (higher is better).

Table 3. Confusion matrix for proprioceptive deficits defined relative to unaffected hand (A) and relative to controls (B). Values are computed with F-M manual assessment of thumb flexion/extension at the interphalangeal joint as the de facto "gold standard." Only the 14 stroke subjects who had F-M data are considered here. Of those 14, the F-M classifies 4 as having a proprioceptive deficit (positives) and 10 as unimpaired (negatives).

	A. Compared to unaffected hand		**B. Compared to controls (mean + 95% CI)**	
	Tablet	**PMDD**	**Tablet**	**PMDD**
True Positives	3	3	3	4
True Negatives	3	6	5	4
False Positives	7	4	5	6
Fales Negatives	1	1	1	0
Sensitivity	0.75	0.75	0.75	1
Specificity	0.3	0.6	0.5	0.4
Positive Predictive Value	0.3	0.43	0.375	0.4
Negative Predictive Value	0.75	0.86	0.83	1

Figure 1

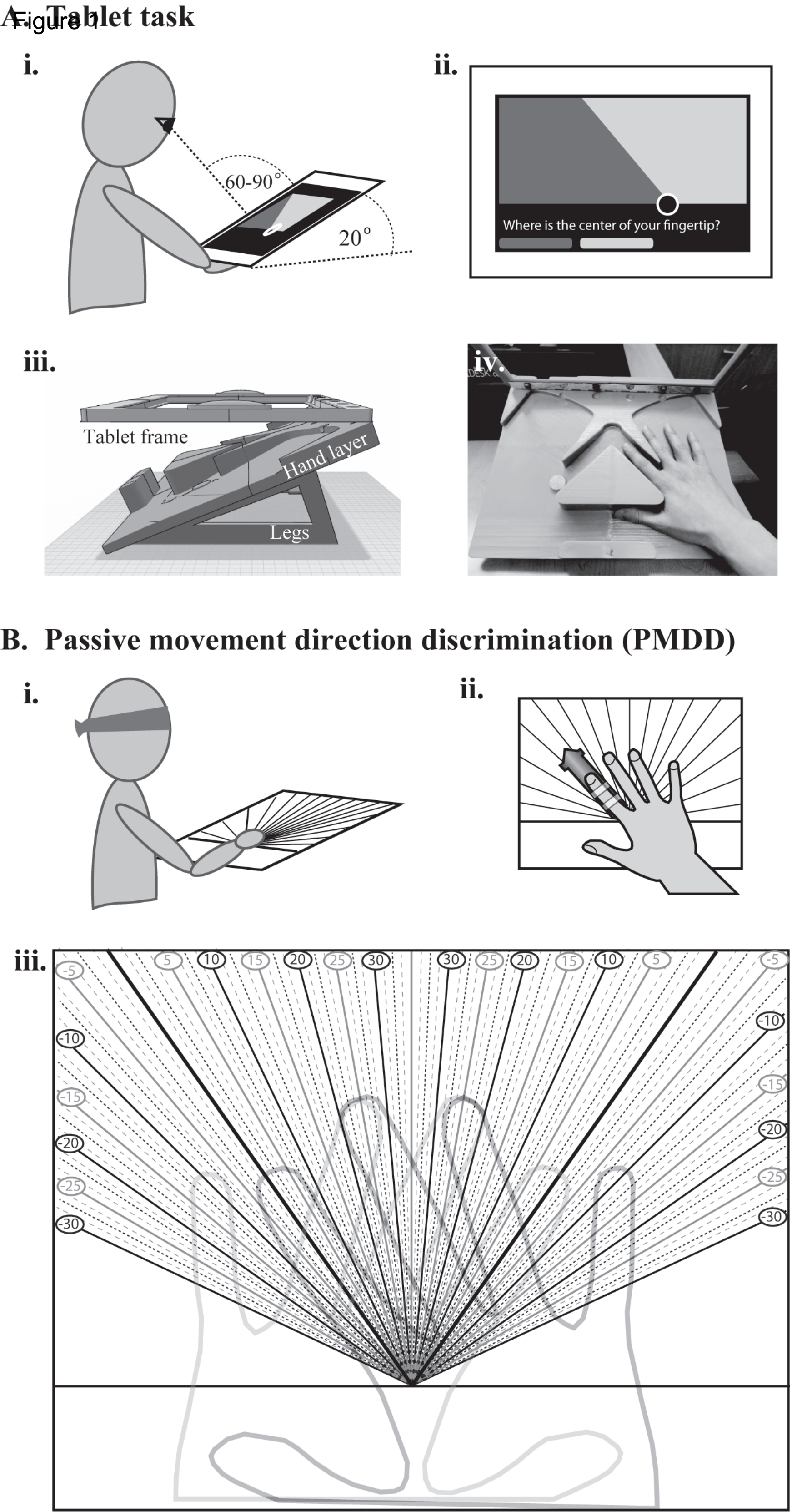

A. Tablet task
i.
60-90°
20°
ii.
Where is the center of your fingertip?
iii.
Tablet frame
Hand layer
Legs
iv.
B. Passive movement direction discrimination (PMDD)
i.
ii.
iii.
-5
5
10
15
20
25
30
30
25
20
15
10
5
-5
-10
-15
-20
-25
-30
-10
-15
-20
-25
-30

Figure 2

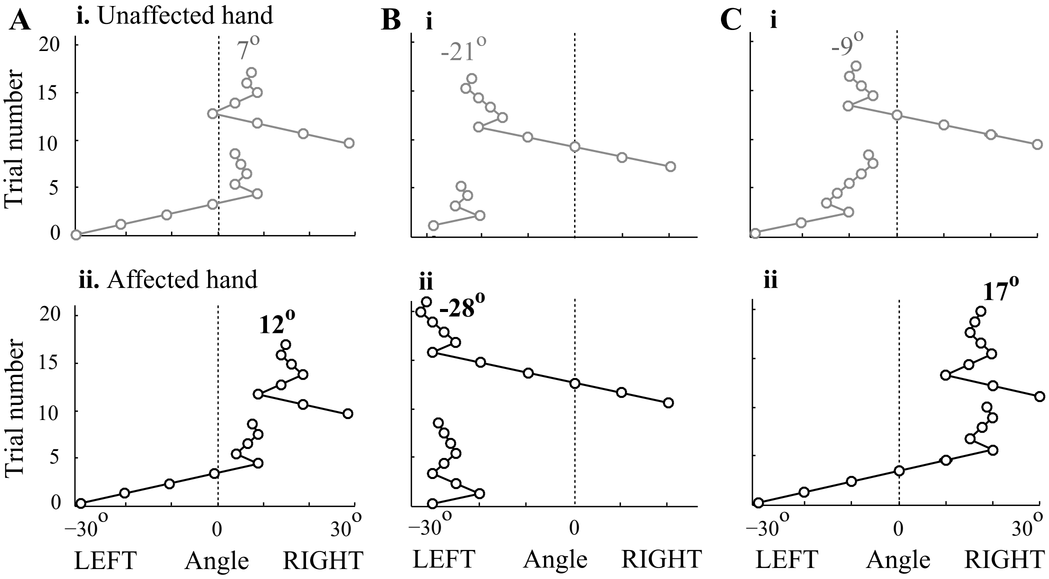

A
i. Unaffected hand
7o
ii. Affected hand
12o
B
i
-21o
ii
-28o
C
i
-9o
ii
17o
Trial number
20
15
10
5
0
−30o
0
30o
LEFT
Angle
RIGHT

Figure 3

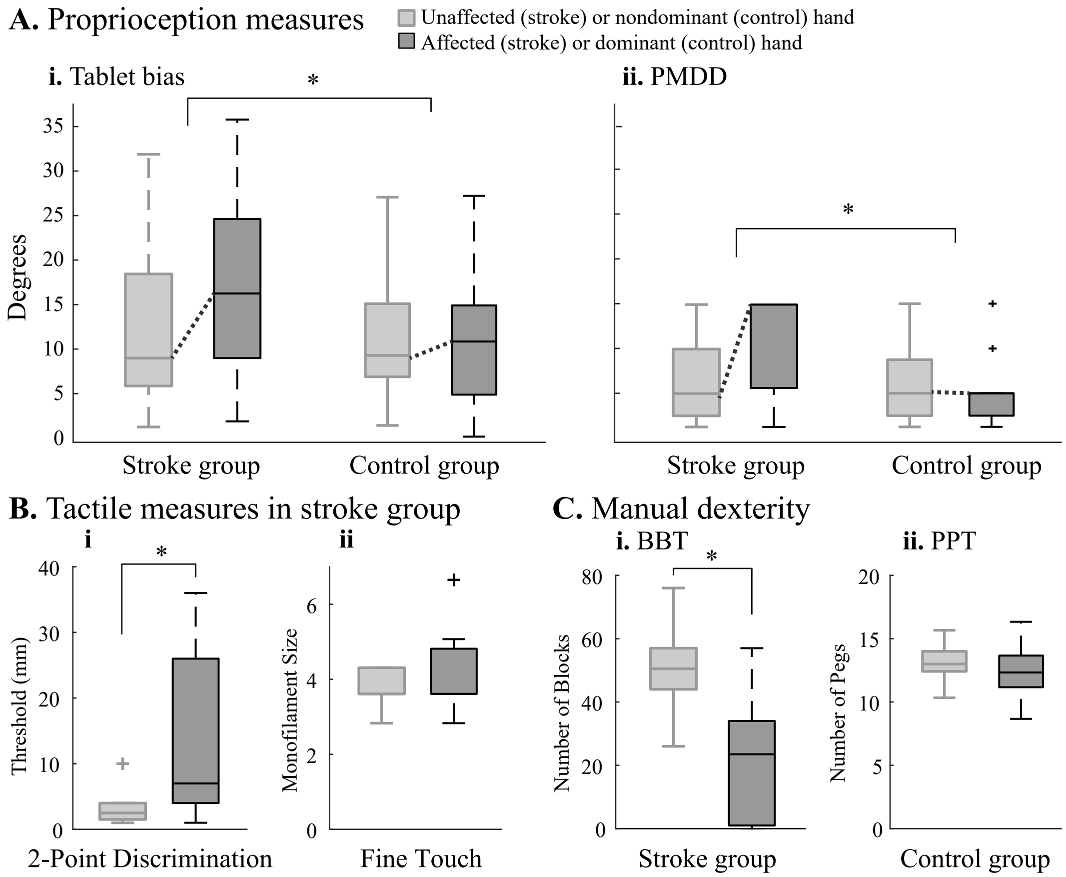
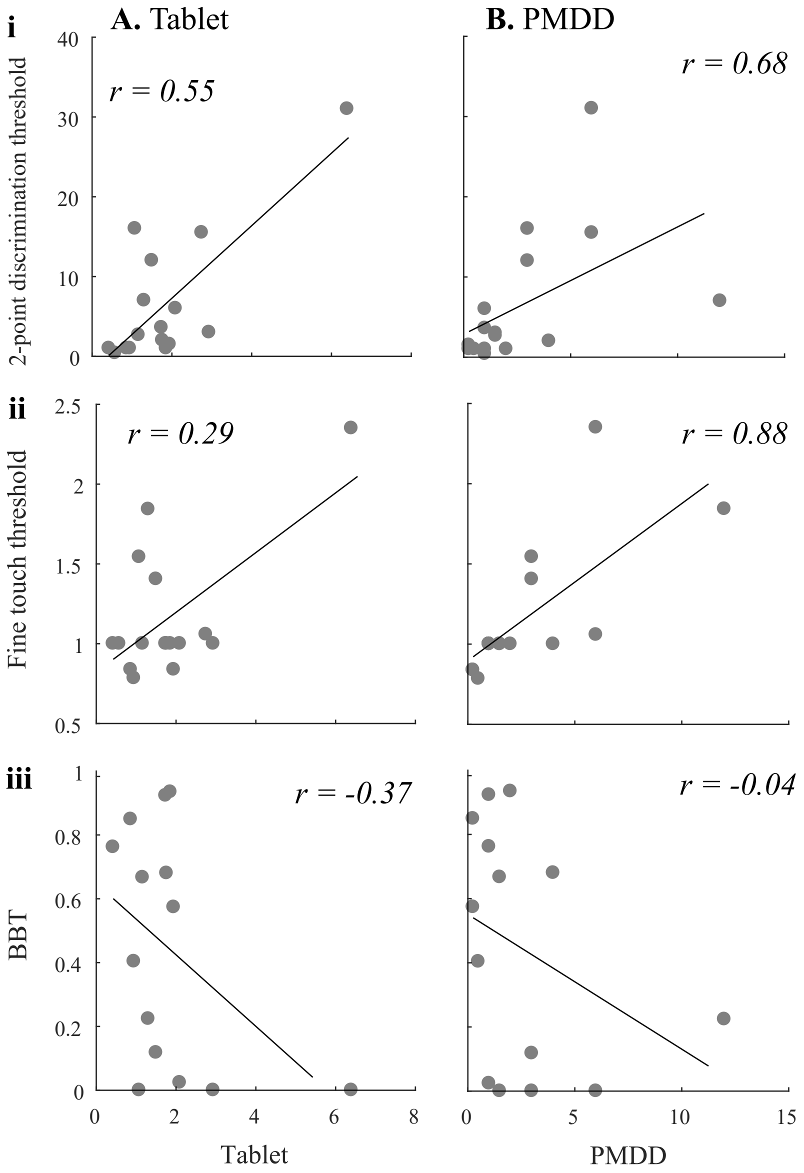

A. Proprioception measures
Unaffected (stroke) or nondominant (control) hand
Affected (stroke) or dominant (control) hand
i. Tablet bias
*
Degrees
0
5
10
15
20
25
30
35
Stroke group
Control group
ii. PMDD
*
Stroke group
Control group
B. Tactile measures in stroke group
i
*
Threshold (mm)
0
10
20
30
40
2-Point Discrimination
ii
Monofilament Size
0
2
4
6
Fine Touch
C. Manual dexterity
i. BBT
*
Number of Blocks
0
20
40
60
80
Stroke group
ii. PPT
Number of Pegs
0
5
10
15
20
Control group

Figure 4



A. Tablet
B. PMDD
i
ii
iii
2-point discrimination threshold
Fine touch threshold
BBT
r = 0.55
r = 0.68
r = 0.29
r = 0.88
r = -0.37
r = -0.04
40
30
20
10
0
2.5
2
1.5
1
0.5
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
0
5
10
15
Tablet
PMDD